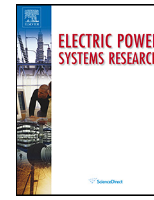
Electric Power Systems Research 140 (2016) 37–45

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Torque ripple minimization in non-sinusoidal synchronous reluctance motors based on artificial neural networks

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ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 21 June 2016
Accepted 26 June 2016
Available online 18 July 2016

Keywords:
Non-sinusoidal synchronous reluctance motor
Torque ripple
Optimal currents
Lagrange optimization
Adaline
Artificial neural networks

ABSTRACT

This paper proposes a new method based on artificial neural networks for reducing the torque ripple in a non-sinusoidal synchronous reluctance motor. The Lagrange optimization method is used to solve the problem of calculating optimal currents in the *d*–*q* frame. A neural control scheme is then proposed as an adaptive solution to derive the optimal stator currents giving a constant electromagnetic torque and minimizing the ohmic losses. Thanks to the online learning capacity of neural networks, the optimal currents can be obtained online in real time. With this neural control, each machine's parameter estimation errors and current controller errors can be compensated. Simulation and experimental results are presented which confirm the validity of the proposed method.

1. Introduction

Synchronous reluctance motor (SynRM) has received much attention for many applications in recent years due to its structural simplicity, low manufacturing cost and rugged construction [1–3]. However, a high level of torque ripple which produces mechanical vibrations and acoustic noise is one of the major drawbacks of this motor.

Torque smoothness is an essential requirement in many applications. Therefore, many authors have proposed different methods to minimize the torque ripple with this kind of machine. In [4], the authors pointed out that there are two approaches that minimize the torque ripple of synchronous motors. The first one consists of techniques to adjust the machine's stator and rotor design in order to cancel the undesirable torque ripple. The authors in [5–7] proposed the methods for reducing the torque ripple by adjusting the flux barrier in rotor structure. The effect of rotor skewing to minimize the torque ripple has been studied in detail [8,9]. The authors in [8] and [9] show that the torque ripple is minimized when the rotor is skewed with an angle which is equal to a stator slot pitch.

The second approach is based on the active control schemes which modify the stator currents and propose the best currents for cancelling the undesired torque ripple. The authors in [10] worked in the *d*–*q* frame in order to calculate the optimal currents. The copper losses in this method are not minimized because the direct current is forced to be equal to the quadrature one $I_d = I_q$. Also working in the d–q reference frames, the works presented in [11–13] give the expressions of optimal currents to minimize the torque ripple. The authors of [11] and [12] propose an extended Park transformation to obtain optimal currents in the non-sinusoidal machine, while the authors in [13] obtain optimal currents to achieve a maximum torque-to-current condition which takes into account the effect of magnetic saturation. Based on input–output linearization, the authors in [14] and [15] propose a method to obtain optimal currents that give the constant torque and minimize the losses. Nonlinear controllers are proposed in [14] to regulate the torque by selecting the product of d-axes and q-axes torque currents as one of the output variables. The cross-coupling effects and iron losses are taken into account in [14]. Based on sliding mode control (SMC) [16], the value of the reference current is adjusted in order

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http://dx.doi.org/10.1016/j.epsr.2016.06.045
0378-7796/

to keep the speed of the motor constant. Therefore, the torque ripple of the motor is minimized. The injection of current harmonic is proposed in [17], the disadvantage of this method is high torque ripple because the authors optimize the currents only for harmonics of ranks 5 and 7. Recently, based on direct torque control (DTC), the works in [18–21] have proposed controlling the stator flux and generating the torque. In [19], the amplitude and angle of the commanding voltage vectors were derived from the errors of torque and flux. Therefore, the torque and flux-ripples are minimized. Based on torque predictive control [20], the optimized voltage is utilized to reduce torque ripple. In that method, the voltage angle vector is determined from the output of torque and flux hysteresis controllers. Another method based on the injection of high-frequency current presented in [21], the MTPA point can be detected because the variation in the torque based on the variation in the current angle is zero at the MTPA points. In [22], the optimal currents are obtained based on emotional controller and space vector modulation (SVM) under an automatic search of the MTPA strategy. In [23], the estimated difference of d–q inductance was used to achieve MTPA control and accurate torque control. While all of these authors work only with sinusoidal machines, in this article we work instead with non-sinusoidal SynRMs.

Unlike the approaches mentioned above, in this article we use an adaptive technique based on artificial neural networks (ANNs) [25,26] to obtain the optimal stator currents. These optimal currents minimize the copper losses and give exactly the electromagnetic torque desired in non-sinusoidal SynRMs. The ANNs presented in this article is the adaline (ADAptive LInear NEuron), which uses an online learning process based on the Widrow–Hoff algorithm. Therefore, the optimal currents are obtained online in real time. Moreover, comparing our copper losses with those from previous methods confirms the validity of the proposed method.

The remainder of this article is organized as follows: torque calculation of the SynRM is presented in Section 2. Section 3 presents the Lagrange optimization method to obtain the optimal currents. The investigation of adaline neural networks for torque and speed controllers is proposed in Section 4. Simulation and experimental results are shown in Section 5 and 6, respectively. Finally, some conclusions are given in Section 7.

2. Torque computation of synchronous reluctance motors

The electromagnetic torque of the SynRM is expressed as:

$$T_e = \frac{1}{2} \cdot i^T \cdot \frac{\partial \left[L(p\theta)\right]}{\partial \theta} \cdot i \tag{1}$$

where $i = \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^T$ is the stator currents vector.

p: the number of pole pairs, and θ: the mechanical angle.

The matrix of inductances $\left[L(p\theta)\right]$ is expressed as follows:

$$\left[L(p\theta)\right] = \begin{bmatrix} L_a(p\theta) & M_{ab}(p\theta) & M_{ac}(p\theta) \\ M_{ab}(p\theta) & L_b(p\theta) & M_{bc}(p\theta) \\ M_{ac}(p\theta) & M_{bc}(p\theta) & L_c(p\theta) \end{bmatrix} \tag{2}$$

where $L_a(p\theta)$, $L_b(p\theta)$, $L_c(p\theta)$: the self- inductances.

$M_{ab}(p\theta)$, $M_{bc}(p\theta)$, $M_{ac}(p\theta)$: the mutual inductances.

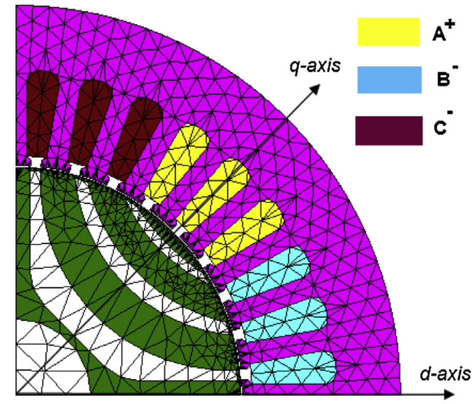

Fig. 1. Meshed FEM model of the studied SynRM by JMAG.

In the case of sinusoidal excitation, the currents vector is expressed as:

$$i = \begin{bmatrix} \sqrt{2}.I_{rms} \cdot \cos\left(p\theta + \varphi\right) \\ \sqrt{2}.I_{rms} \cdot \cos\left(p\theta - \frac{2\pi}{3} + \varphi\right) \\ \sqrt{2}.I_{rms} \cdot \cos\left(p\theta + \frac{2\pi}{3} + \varphi\right) \end{bmatrix} \tag{3}$$

with φ: the load angle. Therefore, in order to maximize the mean value of electromagnetic torque, the load angle is chosen as: $\varphi = 45^\circ$ [10].

An accurate of self and mutual inductances is necessary in the analysis of the SynRM. Because of rotor saliency and stator windings distribution, the self and mutual inductances of a SynRM are non-sinusoidal. The electromagnetic torque produced by this machine presents the torque ripple when it is fed by sinusoidal currents [11], [25].

The measurement of the self and mutual inductances is realized on our laboratory machine test bench. The measurements are done at the stand-still [10,11]. The results of the measurements are compared with the finite element method (FEM) when using JMAG software (see Fig. 1). The comparison of the FEM and measurement results of the self and mutual inductances is shown in the Figs. 2 and 3, respectively. One can be seen that the errors between the FEM and measurement results are not significant.

The expressions of the self and mutual inductances with the significant harmonics are:

$$\begin{cases} L_a\left(p\theta\right) = 0.204 + 0.113\cos\left(2p\theta\right) - 0.0295\cos\left(4p\theta\right) - 0.007\cos\left(6p\theta\right) \\ M_{ab}\left(p\theta\right) = -0.093 + 0.129\cos\left(2\left(p\theta + \frac{2\pi}{3}\right)\right) + 0.01\cos\left(4\left(p\theta + \frac{2\pi}{3}\right)\right) + 0.006\cos\left(6\left(p\theta + \frac{2\pi}{3}\right)\right) \end{cases} \tag{4}$$

The electromagnetic torque obtained with the sinusoidal currents for the SynRM whose parameters are presented in equation (4) is shown in Fig. 4. It can be noticed that the torque ripple is important (around 39% of the required value). Therefore, the optimal currents are thus required for reducing the torque ripple in this SynRM. In the next section, we will present the calculation of optimal currents to achieve MTPA strategy by means of the Lagrange optimization in order to reduce torque ripple.